# TURBO CHANNEL ESTIMATION FOR OFDM SYSTEMS

## BACKGROUND OF THE INVENTION

1.      Field of the Invention

The present invention relates to wireless communication systems and specifically to channel estimation in an orthogonal frequency division multiplexing system.

2.      Discussion of Related Art

Digital multimedia applications are becoming more common as the increase in broadband communication systems continues. While the use of broadband wireless communication develops, a prevailing problem in most digital communication systems includes how to determine the original signal (block of symbols) transmitted when a noisy signal is received. One method, called Orthogonal Frequency Division Multiplexing (OFDM), enables the transmission of symbols at high data rates over hostile channels at a relatively low complexity. The OFDM standard has been adopted in some regions, such as Europe, for radio and TV. The standard is being explored in other contexts such as fixed wireless systems. As with other digital communication protocols, OFDM signals experience the same difficulty in being interpreted at a receiver.

Various channels are presently available for digital communications. These include telephone channels, data channels, broadband channels, satellite channels and fixed wireless channels. There is non-uniformity in the characteristics and bandwidth of these channels and such non-uniformity causes inter-symbol interference that inhibits faster transmission. For example, in applications such as broadband channels and fixed wireless channels, a standard problem increasing the complexity of the system is multi-path channels caused by signals reflected off buildings or other objects between the transmitter and receiver. Multiple versions of the same signal interfere with each other

and cause inter-symbol interference (ISI) with an accompanying lower bit rate. It becomes difficult to extract the original information from the channel with the presence of ISI.

In order for an OFDM system to recognize transmitted signals, the receiver and transmitter must be synchronized. This synchronization involves several tasks. First, timing synchronization involves finding the "beginning" of a received OFDM symbol. The time scales of the transmitter and receiver are synchronized and any extra symbols repeated in the block to preserve orthogonality can be removed with the required accuracy. Second, frequency synchronization is necessary to estimate and compensate for any frequency deviation in the radio carrier frequency assigned to modulate the signal. Third, sampling-clock synchronization provides a conversion of the signal produced by a fast Fourier transform (FFT) of the analog signal into an analog signal assumed to be a certain span of time between two values. Last, if a coherent modulation scheme is used, the channel transfer function $H_{l,k}$ must be estimated and compensated for.

The present invention is most concerned with the channel estimation and compensation process to preserve synchronization in OFDM systems. Channel estimators have been developed with the general purpose of using algorithms to estimate received data sequences at a wireless receiver. The goal of these channel estimators is to produce a computationally and commercially feasible maximum-likelihood (ML) parameter group reflective of the originally transmitted information.

With each block of received data at a receiver, there is unwanted noise that must be taken into account. The process of determining the subject matter on a particular channel may become so computationally complex that various solutions become infeasible. To decrease the complexity, expectation-maximum (EM) algorithms were developed that introduced an iterative process that under some circumstances produce

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maximum-likelihood parameter estimates.   Recovery of transmitted data may be

accomplished using such estimates.

One such method for estimating a channel is discussed in "Sequence Estimation

in the Presence of Random Parameters Via the EM Algorithm," by Costas N.

5      Georghiades and Jae Choong Han (IEEE Transaction on Communications, Vol. 45, No.

3, March 1997, pp. 300-304).  The contents of this paper are incorporated herein by

reference.   In the Georghiades et al. paper, the authors teach about an EM algorithm

wherein optimizing sequence estimates involves two steps:  (1) computing the likelihood

function; and (2) maximizing over the set of all admissible sequences.   The EM

10     algorithm makes use of a log-likelihood function for the complete data in a two-step

iterative procedure that converges to the ML estimation.

Georghiades et al. provide several examples of applying the EM algorithm.  They

discuss the application of the algorithm to the random phase channel in Section III and

the fading channel in Section IV.   Georghiades et al. explain that with respect to the

15     fading channel, they propose applying the EM algorithm to address the computational

difficulties in implementing an optimal receiver in a random-phase case because there is

no obvious way of maximizing the log-likelihood function with respect to the data

sequences having large sequence lengths.

Georghiades et al. teach that applying the EM algorithm to the fading channel

20     involves calculating the expectation step of the EM algorithm using an initial estimate of

the fading vector $\hat{a}_0$, and using the estimate of the fading vector $\hat{a}_0$ to produce, by

maximization, a sequence estimate.   The sequence estimate is then used in another

equation to produce the next fading estimate, and so on, until convergence. Convergence

produces both a sequence estimator and a fading vector estimator.

25     The expectation ("E") portion of the EM algorithm includes computing certain

values and the maximization ("M") step provides a convergence to the true ML estimate.

In the maximizing step, Georghiades et al. note that their algorithm must maximize by maximizing each individual term in the sum, i.e., by making "symbol-by-symbol decisions." To improve the efficiency of the algorithm when maximization must be performed on a symbol-by-symbol basis, the Viterbi algorithm is used when trellis coding is present. However, when trellis coding is not present, Georghiades et al. seek to increase efficiency by fixing the number of iterations to two with only "very little performance loss."

The method described by Georghiades et al. is deficient in several respects. First, it only addresses a single antenna scenario. Further, the approach by Georghiades et al. only addresses re-estimation using all the compensated data symbols for Phase Shift Key (PSK) modulation. In this regard, the approach by Georghiades et al. maintains a high degree of computational complexity that prevents efficient use of the EM algorithm for channel estimation, especially when the number of data symbols in a block or frame is large.

Furthermore, the Georghiades et al. approach is limited to the PSK modulation using a single antenna receiver. Their approach is not well suited to Orthogonal Frequency Division Multiplexing (OFDM), wherein the data-stream is split into multiple RF channels, each of which is sent over a sub-carrier frequency. The S/N ratio of each of the channels in OFDM is precisely defined and is carefully monitored to ensure maximum performance.

Other related patents teach different techniques for channel estimation. For example, U.S. Patent No. 5,465,276 to Larsson et al., which contents are incorporated herein by reference, teaches a method of adaptive tracking for a fast time-varying channel with no feedback mechanism. The channel estimate taught in the '276 patent uses an estimated time derivative of the channel estimate that is adapted with the aid of the decided symbols. The channel estimate is adapted to the radio channel by the derivate

estimate and the decided symbols. The approach of the '276 patent addresses a rapidly

varying signal strength and fading where the channel estimate, predicted mainly through

the derivative estimate, varies relatively evenly.

The '276 patent is not well suited to the OFDM system where the wireless

5    channel remains quasi-constant over a block of symbols because it would then provide

needless derivative computations.

U.S. Patent No. 5,687,198 to Sexton et al. teaches a method of estimating a

channel by first taking an initial channel estimate using pilot symbols and compensating

all the data symbols. The '198 patent next teaches taking a group of samples and

10    computing a vector average of the group of samples. Each sample is then compared to

the vector average and the largest sample is retained and the others are discarded as

noise. After receiving a predetermined number of retained samples, a new channel

estimate is generated containing fewer errors than previously would have been obtained

if the noisy samples had been retained.

15    The '198 patent fails to adequately address the deficiencies in the art where all of

the data symbols must be compensated for in the first channel estimate, thus increasing

the computational complexity of the channel estimation process.


## SUMMARY OF THE INVENTION

20    What is needed in the art is a method and system for performing accurate

channel estimation in an OFDM system wherein the wireless channel remains quasi-

constant over a block of symbols. Further what is needed is a system and method

capable of use with multiple receiver antennas. Further what is needed is a system and

method of increasing the efficiency of channel estimation by choosing and compensating

25    a subset of the strongest data symbols from a set of received data symbols in the iterative

process.

The present invention addresses the deficiencies of the prior art by increasing the accuracy and efficiency of channel estimation in several respects. First, the present invention comprises choosing a subset of symbols from the set of symbols received by the receiver and compensating only the subset in the iterative process of estimating the

5    channel. The present invention further is particularly well suited to the OFDM system because of its broadband application and because the present invention reduces the structural and computational complexity which hinders the performance of OFDM systems. In OFDM systems, broadband transmission is decomposed into many parallel narrowband transmissions. The channel is flat and varies slowly relative to each

10   narrowband transmission. In this regard, the present invention is particularly well suited to channel estimation in OFDM broadband systems.

According to the first embodiment of the present invention, a wireless system having a receiver comprises a channel estimator associated with the receiver. An initial estimator and a symbol selector provide data to a symbol compensator, which outputs its

15   data to the channel estimator. The channel estimator is operable to receive a block of "n" transmitted symbols. These symbols may also be referred to as frequency tones. The symbols include "p" pilot symbols and "d" data symbols. The initial estimator uses the pilot symbols to estimate a wireless transmission channel to obtain an initial estimate and the symbol selector chooses the "m" strongest symbols from the received "d" data

20   symbols. Preferably, "m" is less than "d" such that the number of symbols chosen is less than the total number of symbols received. The symbol compensator compensates the group of "m" strongest symbols using the initial estimate and re-estimates the channel using the compensated symbols and pilot symbols. The value of "m" may also be chosen to equal "d" in order to achieve best channel estimate at the cost of

25   computational complexity.

The channel estimator next will either repeat the steps of choosing the group of "m" strongest symbols, compensating the "m" strongest data symbols and re-estimating the channel, or using a latest channel estimate to compensate all the symbols within the block. The functionality of the present invention may be implemented in the wireless

5 receiver wherein the channel estimation functionality is programmed, for example, using a digital signal processor (DSP) or an application specific integrated chip (ASIC) and imbedded into the wireless system design software for accomplishing the steps set forth herein. One of ordinary skill in the art will understand the necessary hardware components to implement the present invention.

10 The second embodiment of the present invention relates to a method of estimating a channel in a wireless receiver. The method comprises receiving a block of "n" transmitted symbols, the symbols including "p" pilot symbols and "d" data symbols, using the pilot symbols to estimate a wireless transmission channel to obtain an initial estimate, choosing a group of "m" strongest symbols from the "d" received symbols,

15 compensating the "m" strongest symbols using the initial estimate, and re-estimating the channel using the compensated symbols and pilot symbols. Finally, the method comprises either repeating the steps of choosing "m" strongest symbols, compensating the "m" strongest symbols and re-estimating the channel, or using a latest channel estimate to compensate all symbols within the block. Preferably, according to the second

20 embodiment of the invention, "m" is less than "d", although that is not a requirement of the invention.

In another aspect of the second embodiment of the invention, after the "m" strongest symbols are chosen and compensated, and a channel re-estimate is performed, if a predetermined number of iterations has not yet occurred, another set of "x" symbols

25 are chosen for compensation. Preferably, "x" is less than "m" but it may also be equal to or greater than "m". Preferably, the "x" strongest symbols are chosen for another

iteration of compensating symbols. The "x" set of symbols may be chosen to further

refine the compensation of symbols in preparation for the step of re-estimating the

channel using compensated data symbols and the pilot symbols.


**BRIEF DESCRIPTION OF THE DRAWINGS**

The foregoing advantages of the present invention will be apparent from the

following detailed description of several embodiments of the invention with reference to

the corresponding accompanying drawings, in which:

FIG. 1 illustrates the first embodiment of the present invention in a multiple

10    antenna scenario;

FIG. 2 illustrates the second embodiment of the invention;

FIG. 3a illustrates an aspect of the second embodiment of the invention;

FIG. 3b illustrates yet another aspect of the second embodiment of the

invention; and

15        FIG. 4 illustrates a variation on the second embodiment of the invention.


                            **DETAILED DESCRIPTION OF THE INVENTION**

The present invention may be understood with reference to the drawings. FIG. 1

illustrates the first embodiment of the invention. A communication system receiver 100

20    comprises an analog front-end having two antenna receivers 102 and 104 for receiving

data $r_1$ and $r_2$ respectively. The respective RF front ends 106 and 108 receive the signal

where they are synchronized and demodulated from the OFDM signals as shown in

blocks 110 and 112. As is known, the received signals $r_1$ and $r_2$ will experience different

fading characteristics and their average strengths for $r_{1d}$ and $r_{2d}$ (the received signals $r_1$ and

25    $r_2$ after they are OFDM demodulated) are different.

The demodulated data from block 110 is transmitted to an initial channel estimator 116 and a symbol selector 120. Similarly, the demodulated data from block 112 is transmitted to an initial channel estimator 118 and a symbol selector 120. The $r_{1d}$ demodulated data is delayed 122 and the $r_{2d}$ demodulated data is delayed 124. The

5 symbol selector 120 performs three basic steps. First, the selector 120 compares the signal strengths between $r_{1d}$ and $r_{2d}$ using means known to those of skill in the art, such as maximum signal strength, average signal strength, or using the first signal strength received by the two antennas. Depending on the comparative method used, the selector 120 chooses the strongest set of signals. Next, from the stronger set of signals, the

10 selector chooses the strongest data symbols based on the individual data symbol's strength. Finally, the selector 120 chooses data symbols from the weaker signal sequence at frequency tone positions corresponding to the selected data symbols from the strongest signal sequences. Both sets of data symbols are transmitted to a symbol compensator 126 to recover the original symbols using diversity combining or beam

15 forming techniques.

The symbol compensator 126 performs compensation for the initial estimated data and the symbols selected by the symbol selector 120. Preferably, the symbol selector 120 is programmed to select the "m" strongest data symbols from the stronger sequences of the received sequences $r_{1d}$ and $r_{2d}$. The symbol compensator 126 recovers

20 the selected data symbols by using diversity combining, such as maximal ratio combining (MRC) or minimum mean squared-error (MMSE) combining, or beam forming techniques. Other techniques may be used and are known to those of skill in the art.

While only two input antennas 102, 104 are shown, the present invention may include more than two antennas to further improve the compensation performance of

25 the system. In such a case, the symbol selector 120 will be modified to determine the relative strengths of the various sequences received and make determinations of which is

the strongest sequence from which to choose the "m" strongest data symbols. Various combinations of the concept of using the frequency tone positions from the strongest sequence for choosing "m" data symbols at the same frequency tone positions from the weaker sequences may be used. For example, if four data sequences were received from

5 four receiving antennas, then the strongest data sequence may be used for choosing the "m" strongest data symbols and "m" symbols will be chosen from the three weaker data sequences at the same frequency tone positions. Or, of the four sequences received, the symbol selector 120 may choose the two strongest sequences (say, for example, the first and third) and make calculated decisions regarding which data symbol frequency tone

10 positions to use for choosing data symbols from the second and fourth sequences, i.e., whether the "m" strongest data symbol frequency tone positions from the first sequence will be used to choose "m" data symbols from the weaker second sequence, and the "m" strongest data symbols from the third sequence will be used for choosing the "m" data symbols at the same frequency tone position from the weaker fourth sequence.

15 The compensated symbols are transmitted to the channel re-estimator 128 that produced a channel estimation result "h". Following the channel estimation 128, iterative loops may be used to repeat the steps of symbol selection, 114, 120, symbol compensation 126 and channel re-estimation 128. A predetermined value of "T" may be programmed for controlling the number of iterative loops. The system 100 will continue

20 to iterate until the value of "T" is met or exceeded. Once the value of "T" is met, the latest channel estimation "h" may be used by the data symbol compensator 130 for recovering data symbols that are transmitted to a demodulator and decoder (not shown) to obtain the original binary sequences.

Further, in the iterative process, a different value from "m" may be used

25 following the first pass-through. For example, the channel estimator (or re-estimator) 128 or the symbol selector 120 may determine a value of "x" after the first pass-through

and if the number of iterations "T" has not been met. The value of "x" would preferably be less than "m" but may be equal to or greater than "m". The "x" strongest symbols may then be chosen by the symbol selector 120 and used for symbol compensation 126 and channel re-estimation 128.

5      FIG. 2 illustrates a second embodiment of the invention related to a method of estimating a channel in a wireless receiver. The steps outlined in FIG. 2 are for illustration only and are not meant to be limited to the exact order or procedure but set forth the general concept of the invention. First, the receiver receives a block of "n" transmitted symbols (200). The symbols preferably include pilot symbols and may

10    include "d" data symbols. Using the pilot symbols, a wireless channel is estimated (202). If this is the first pass through the estimation and compensation process, then the channel estimate at this stage may be referred to as an "initial" estimate. A set or group of "m" strongest symbols is chosen from the received "d" data symbols (204). Next, the "m" strongest symbols are compensated (206) using the channel estimate from step 202.

15    The strongest symbols are determined by signal strength or by using a predetermined signal-to-noise ratio.

When multiple receive antennas are used as shown in FIG. 1, diversity combining or beam forming may be utilized to improve the compensation performance in step 206. Following compensation, the method comprises re-estimating the channel using the

20    compensated symbols and pilot symbols (208).

The symbols chosen to be part of the group in step 204 are determined preferably on signal strength. A predetermined criteria will preferably be established in which symbols in the block having a signal strength above the criteria will be chosen to be in the group of "m" symbols to be compensated. However, other criteria may also be

25    set for determining which symbols will be compensated.

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Following the re-estimation of the channel, the method determines whether a pre-determined number of iterations, "T", have occurred. If the number of iterations is less than "T" (210), the process returns and proceeds again at step (204). If the number of iterations is equal to or greater than "T" as determined in step (210), then the process

5    uses a latest channel estimate to compensate all data symbols within the block (212). Step 210 may be equivalently asked as whether the number of iterations is greater than or equal to "T" or whether the number of iterations is less than "T." The different branches from step 210 of course will flip-flop between "yes" and "no" depending on how the system is programmed to ask the question. According to the preferred aspect

10   of the second embodiment of the invention, "m" is less than "d." However, in another aspect of the invention, "m" equals "d." The choice for the value of "T" may be based on a number of factors, such as the DSP Mips requirements.

FIG. 3a illustrates yet another aspect of the second embodiment of the invention. Steps 200 through 210 are the same as those shown in FIG. 2. FIG. 3a illustrates a

15   different branch of the method after block 210. As shown in FIG. 3a, if the number of iterations is less than "T" (210), then a number "x" of the strongest symbols are chosen (214). The "x" strongest symbols are compensated and the process proceeds to step 208 where the channel is re-estimated using the "x" number of compensated symbols and the pilot symbols. The value of "x" is preferably less than "m" in this example.

20   As shown in FIG. 3a, if the number of iterations is equal to or greater than "T", then the process continues to use the latest channel estimate to compensate all the symbols within the block (212). With the new branch introduced in FIG. 3a, the process may be more efficient by continuing to narrow down the strongest symbols used for compensation.

25   In FIG. 3b, a variation on the method shown in FIG. 3a is illustrated. In this aspect of the second embodiment of the invention, steps 200-210 are the same as that

shown in FIG. 2, and a new branch is shown stemming from step 210. In FIG. 3b, if the

number of iterations is less than "T" (210), then a value of "x" is chosen (218). If "x" is

less then "m", then the method proceeds to steps 214 and 216 as shown in FIG. 3a.

However, if "x" is equal to or greater than "m" (220), then "m" is set equal to "x" and

5    the method proceeds at step 204 with choosing a group of the "m" strongest symbols

from the "d" received symbols. The value of "x" may equal "m" and may be either

greater than or less than "m." In this regard, for efficiency purposes, if "x" is less than

"m", a smaller number of symbols may be chosen from the block for the repeated step

of choosing a group of strongest symbols to compensate and use for channel estimation.

10   Similarly, if predetermined criteria indicate, "x" may be greater than "m" in order to have

a larger group of the strongest symbols compensated in the iterative process.

Another aspect of the second embodiment of the invention, shown in FIG. 4,

relates to step 204: choosing a group of "m" strongest symbols for compensation. In

broad terms, as set forth above, a subset of "m" of the strongest symbols are chosen.

15   However, other methods of choosing and transmitting a set or sets of data symbols to a

symbol compensator for data recover may be employed.

One such system has been described above in connection with the first

embodiment of the invention. This variation on step 204 is shown in FIG. 4 and is

preferably performed by the symbol selector 120. The selector 120 compares the signal

20   strengths between $r_{1d}$ and $r_{2d}$ using means known to those of skill in the art, such as

maximum signal strength, average signal strength, or using the first signal strength

received by the two antennas. Depending on the comparative method used, the selector

120 chooses (302) the strongest set of signals. Next, from the stronger set of signals, the

selector chooses the strongest data symbols based on the individual data symbol's

25   strength (304). Finally, the selector 120 chooses data symbols from the weaker signal

sequence at the corresponding frequency tone positions as the selected data symbols from the strongest signal sequences (306).

Both sets of data symbols are transmitted to the symbol compensation block 126 to recover the original symbols using diversity combining or beam forming techniques. While the example shown in FIG. 4 relates to two received sets of data sequences, the present invention may be expanded to include a plurality of signal sequences received from a plurality of receiving antennas. In such case, the concept of choosing a strongest set of sequences of the received sequences and using a subset of "m" strongest symbols from the chosen sequence may be modified to apply in various ways to systems with more than two antennas.

The method may be implemented using a system comprising a wireless receiver having an estimator unit programmed, for example, using a DSP or an ASIC and imbedded into the wireless system design software for accomplishing the steps set forth according to the various aspects of the method. This implementation will be understood by one of skill in the art with the information provided herein regarding the invention.

Although the above description may contain specific details, they should not be construed as limiting the claims in any way. Other configurations of the described embodiments of the invention are part of the scope of this invention. Accordingly, the appended claims and their legal equivalents should only define the invention, rather than any specific examples given.